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# VULNERABILITY OF TRANS-CARPATHIANS ROAD NETWORK

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***Abstract:*** *The modernizing and extension of road transport infrastructures according to land use and sustainable development requirements still represent a challenging issue among policy makers, regional/local authorities and scientists. The concepts of reliability and vulnerability are important when investigating the ability of road transport networks to provide continuity in operation and maintaining the level of service between acceptable limits. The two concepts are discussed in a complementary way, outlining the specific features of each one. Reliability is described under connectivity, travel time and capacity aspects, whereas vulnerability is analyzed through the consequences of links or nodes failure, irrespective of the probability of failure, and mainly through changes of Hansen index of accessibility and users total cost. The case study investigates the Romanian Trans-Carpathian road network vulnerability related to transport costs and assesses the importance of road network links and nodes exposure.*

**Keywords**: critical infrastructures, transport network vulnerability, accessibility.

## RELIABILITY AND VULNERABILITY – INTERCONNECTED CONCEPTS

The concepts of reliability and vulnerability are quite important in assessing the ability of transport networks to provide continuity in operation. Transport networks are exposed to various factors that can lead to decrease of serviceability. Bråthen and Lægran [1] identify three categories of network attributes or features responsible for its disruption:

- *Structural features* relate to network topology, connectivity, infrastructure physical body, curvature, art works, weight restrictions etc.
- *Natural factors* take into consideration the attributes of the natural environment (land topography), the natural incidents (flood, avalanche, rock fall, snowing and icing, fog, earthquake) and climate changes.
- *Traffic attributes* refer to traffic flows (transport demand, O-D matrix, route choice, links debit, peak-hours and weekend/season variability) as well as maintenance operations, construction sites and accident clear-up.

None of these three aspects acts on individual basis. Even though a specific failure addresses one of these aspects, the entire network could be exposed to the full set of determinant factors. Reliability and vulnerability assessment should consider each attribute separately and, at the same time, as a whole. The impact of nodes or link disruption could be quite significant. The transport planners or policy makers need methods and decision support tools to evaluate threats to transport networks facilities and to assess the consequences of network functionality disruption and failure of its elements.

Economic, social and environmental benefits come from the possibility to evaluate, manage and minimize the impacts of transport networks degradation. The reliability of transport networks elements is a probabilistic measure that refers their ability not to fail or malfunction, during a specific period, given a set of performance guidelines [2]. Even if some elements of the transport network are failed, the network could remain functional although with less performances.

One differentiates three forms of network reliability [3, 4]:

- *connectivity reliability* – the probability that two nodes in a network remain connected, i.e. there still is a path connecting them when a set of links have been cut off;
- *travel time reliability* – the probability that a trip between an origin and a destination node can be completed within a given time interval; the travel time can be affected by the imperfect knowledge of drivers and variation of link flows due to route choice decision;

- *capacity reliability* – the probability that a network can accomplish a given level of travel demand, i.e. the reserve capacity can accommodate the required demand for a specific capacity loss due to network degradation.

In contrast to reliability, the concept of vulnerability is related to the consequences of network elements failure, irrespective of the probability of failure. It is possible that a link failure may have a very small probability, but when the event occurs, the adverse social, economic and environmental impacts may have such an intensity to indicate a major problem. Vulnerability analysis provides a way to find structural weakness in the network topology that makes it vulnerable to consequences of failure or degradation. Taylor and D'Este [5] distinguish two forms of vulnerability in transport networks:

- *accessibility vulnerability* – a node is vulnerable if the failure of a small number of links in the network results in a severe decrease in the accessibility of that node;
- *cost related vulnerability* – if the degradation of one or more links on a path connecting two nodes leads to substantial increase of the generalized cost of travel between them, then the connection between those nodes is vulnerable.

## TRANSPORT NETWORK VULNERABILITY

### Accessibility vulnerability

Taylor and D'Este [5] use accessibility and Hansen accessibility index to characterize transport networks vulnerability. The accessibility of a node *i* is

$$A_i = \sum_{j \neq i} B_j f(c_{ij}), \quad (1)$$

where $B_j$ is the attraction measure of node *j*, $c_{ij}$ represents the generalized cost of travel from node *i* to *j* and $f(c_{ij})$ the impedance function of the journey. Usually, the impedance function is the inverse of the generalized cost of travel (distance, time or money units) or a negative exponential function.

The Hansen index of node accessibility is defined by

$$HA_i = \frac{\sum_{j \neq i} B_j f(c_{ij})}{\sum_{j \neq i} B_j}, \quad (2)$$

and the accessibility index for the entire network is

$$TA = \sum_i HA_i \,. \quad (3)$$

An incident occurred in the network that causes the failure of the link *k* results in nodes and network accessibility decreasing:

$$\begin{aligned} \Delta HA_i &= HA_i^{(0)} - HA_i^{(k)}, \\ \Delta TA &= TA^{(0)} - TA^{(k)}. \end{aligned} \quad (4)$$

where the index ($^0$) refers to the undamaged network and the index ($^k$) to the network with the link *k* inoperable.

Relative variation of accessibility for nodes and the whole network could also be computed:

$$\begin{aligned} \%\Delta HA_i &= \frac{HA_i^{(0)} - HA_i^{(k)}}{HA_i^{(0)}}, \\ \%\Delta TA &= \frac{TA^{(0)} - TA^{(k)}}{TA^{(0)}}. \end{aligned} \quad (5)$$

### Cost related vulnerability

Jenelius et al. [6] use, as a measure of reduced performance of the transport network, the increase in the generalized cost of travel (time, distance, money) for the users. When a link *k* is closed, the network may be divided into several disconnected parts, so that a number of trips from origin *i* are not able to reach the destination *j*. Thus results an unsatisfied demand

$$u_{ij}^{(k)} = \begin{cases} \varphi_{ij} & \text{if } c_{ij}^{(k)} = \infty \\ 0 & \text{if } c_{ij}^{(k)} \neq \infty \end{cases}, \quad (6)$$

where $\varphi_{ij}$ represents the travel demand from node *i* to node *j* and $c_{ij}^{(k)}$ is the generalized cost of travel from node *i* to *j* when link *k* is closed.

Therefore, there is a dichotomy of the link importance according to travel cost increasing and unsatisfied demand into the network. If the link *k* belongs to the set of non-cut links ($L^{n-c}$), the importance of the link *k* for the whole network is

$$\Omega(k) = \frac{\sum_i \sum_{j \neq i} \varphi_{ij} (c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_i \sum_{j \neq i} \varphi_{ij} c_{ij}^{(0)}}, \quad (7)$$

where $c_{ij}^{(0)}$ is the generalized cost of travel from node *i* to node *j* in the undamaged network.

The importance regarding the unsatisfied demand of a link *k* is

$$\Omega_{uns}(k) = \frac{\sum_i \sum_{j \neq i} u_{ij}^{(k)}}{\sum_i \sum_{j \neq i} \varphi_{ij}}. \quad (8)$$

In addition, the link disruption is translated into nodes exposure. The demand weighted exposure of node *i* is the maximum value over all non-cut links:

$$\Phi(i) = \max_{k \in L^{n-c}} \frac{\sum_{j \neq i} \varphi_{ij} (c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_{j \neq i} \varphi_{ij} c_{ij}^{(0)}}. \quad (9)$$

The exposure regarding the unsatisfied demand for the node *i* is

$$\Phi(i) = \max_k \frac{\sum_{j \neq i} u_{ij}^{(k)}}{\sum_{j \neq i} \varphi_{ij}}. \quad (10)$$

**ASSESSING ROMANIAN TRANS-CARPATIANS ROAD NETWORK VULNERABILITY**

Transport infrastructure, and especially road and railway networks are in continuous expansion and reshaping at European level. The investments in transport infrastructure represent a core in the budget of each member state. Comparing to new comers, Romania still faces a delay in the absorption of EU structural convergence funds. Despite its direct connection with EU, Romania has a marginal geographic position. The transport Pan-European corridors (IV and IX) are crossing Romania, but their international use on the national sector is still reduced due to:

- unsatisfactory infrastructure physical body;
- reduced possibilities to run on high-ways or high-speed railways;
- crossing through many rural and urban centers;
- lack of detour roads of the great urban areas;
- level of transport services.

Among the directions of the sustainable development of Romania, the transport system restructuring represents a priority because it generates externalities for the environment and local communities. At the same time, Romania barely satisfies the economic equity of a sustainable transport system. The OECD [7] vision of a sustainable transport is defined in term of accessibility, namely the possibility to access spaces, goods, and services. For Romania, this principle still represents a distant desiderate. The metropolitan and regional polarization results in the isolation of a great number of local communities and increasing time and distance to access to jobs, medical care, social/cultural life or tourist points [8]. The desert of rural space is an acute phenomenon. As figure 1 shows, the commodities flows on Romanian road network are highly polarized.

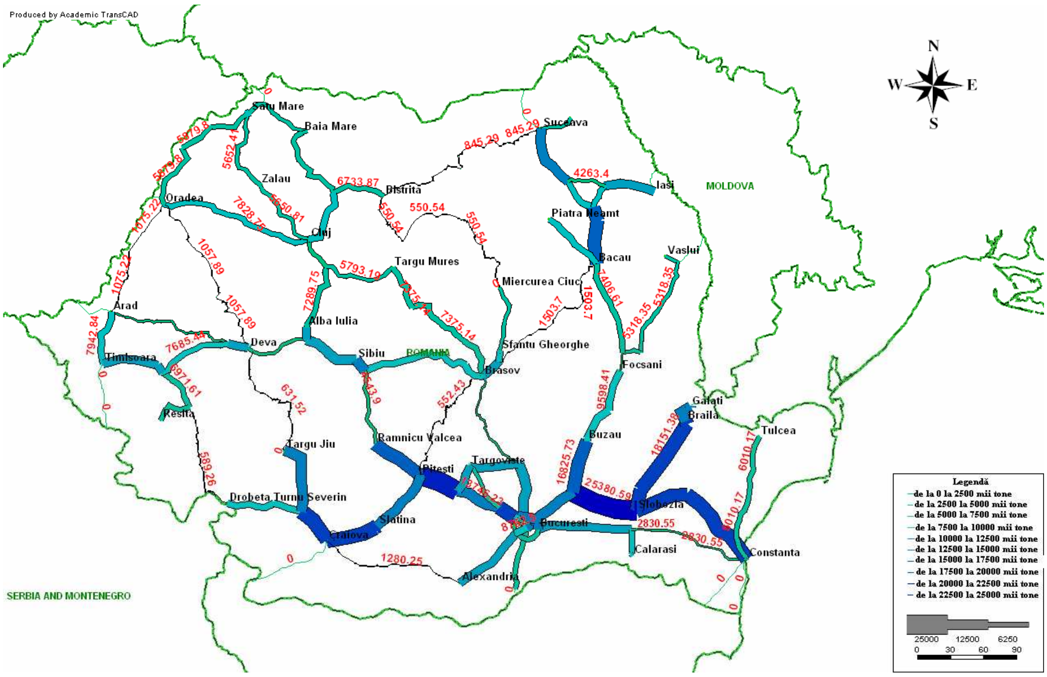


**Fig. 1. Commodities flows on Romanian road transport network**

Part of the IV[th] Pan-European corridor is used to connect the industrialized zones from the South of Romania with Bucharest and Constantza maritime port. The commodities flows in East and West sides of the country are concentrated around the most important regional economic centers. In contrast, feeble flows are registered between the historical regions, as a proof of the weak accessibility of the Romanian road network, with negative influences on sustainable economic development. The poor density, connexity and connectivity of the road transport network are responsible for its vulnerability to structural, natural and traffic factors.

The Trans-Carpathians road network links represent critical infrastructure elements. The disruption of their functionality generates increasing of transport costs in the whole network. The hierarchy of the links importance, determined by the relative variation of transport costs (eq. 7) is depicted in figure 2.

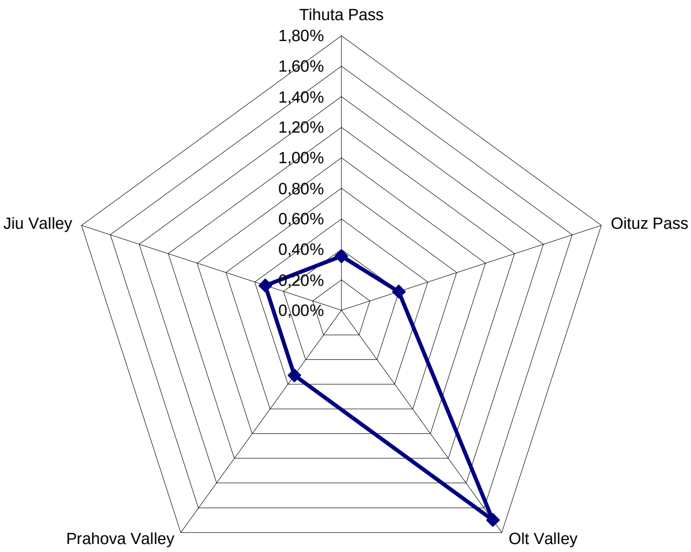


**Fig. 2. Trans-Carpathians road links importance**

For the present transport flows, the disruption of transport on Olt Valley generates an increasing with almost 2% of the transport costs at global level. Smaller variations are produced by the non-functionality of the other Trans-Carpathians links. For regional nodes located in the proximity of the Olt Valley, the disruption of this link engenders their exposure. The relative variation of Hansen accessibility index for several nodes is shown in figure 3.

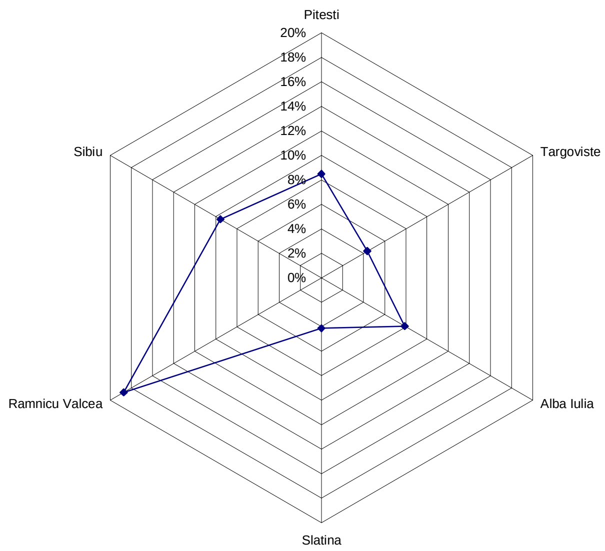


**Fig. 3. Accessibility relative variation for nodes located in the proximity of Olt Valley**

## CONCLUSION

Road transport network reliability and vulnerability demand an integrated approach. Both technical and non-technical factors are of great importance. Assessment methodologies based on multiple perspectives are recommended. Proactive measures are needed in order to prevent disruptions and to assure that the network will be able to maintain an acceptable level of service. It is important to prevent the network from failure, but if this occurs, it is also important to minimize the extent of the negative effects and to restore the normal state as quick as possible. The methods presented are useful for transport planners and traffic engineers in focusing their efforts in refining techniques for identifying network weakness, evaluating cost-effective risk management and remedial responses such as reducing risk profile, modernizing current infrastructure, creating alternative routes and minimizing socio-economic impacts in terms of location and accessibility to markets, services and facilities. Romanian Trans-Carpathians road links represent critical points of the road network, along with Danube crossing points. Their disruption can cause important externalities in terms of accessibility decreasing and transport cost increasing at global level. The presence of large industrial areas in the proximity of Trans-Carpathians roads (oil, chemical, automotive) leads to their exposure to network failure and delays in supplying essential goods (food, manufacturing, utilities etc.). Romanian road network is mainly sensitive to structural and natural factors of disruption. The poor connectivity, the old infrastructure physical body and the weak maintenance operations along with natural disasters due to climate change still represent real threats for road network. Local communities and regional isolation due to flood, snowing or rock fall counted during the last decades are quite significant. Thus, improving road transport network serviceability jointly with integrated systems for risks management should be further developed.

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